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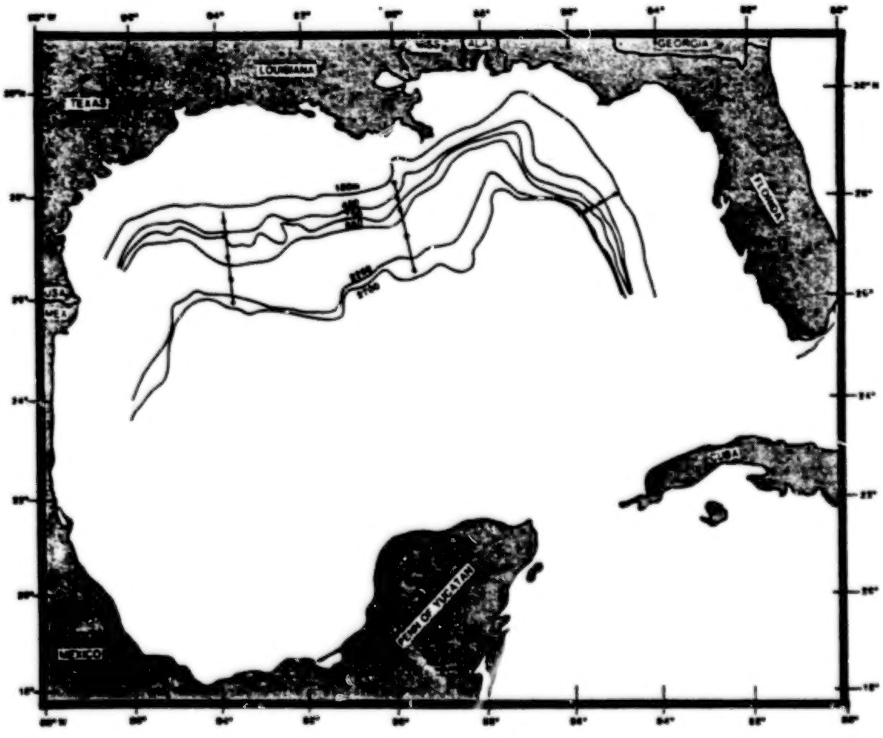
OCS STUDY
MMS 85-0058

EXECUTIVE SUMMARY OF THE ANNUAL REPORT FOR NORTHERN GULF OF MEXICO CONTINENTAL SLOPE STUDY



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OCS STUDY
MMS 85-0058

EXECUTIVE SUMMARY

NORTHERN GULF OF MEXICO CONTINENTAL SLOPE STUDY

by

LGL Ecological Research Associates, Inc.
1410 Cavitt Street
Bryan, Texas 77801

and

Texas A&M University
College Station, Texas 77843

Prepared under Contract No. 14-12-0001-30046

for

Minerals Management Service
Gulf of Mexico OCS Regional Office
3301 N. Causeway Boulevard
Metairie, Louisiana 70002

May 1985

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INTRODUCTION

The continental slope of the Gulf of Mexico is poorly known from an ecological standpoint, but is a habitat into which oil and gas exploration and development activity is proceeding at an accelerating rate. In response to its mandate to obtain environmental data on the impacts of petroleum development on the outer continental shelf (OCS) and provide the relevant information to decision makers, Minerals Management Service (MMS) contracted in late 1983 a four-year research program to investigate the slope habitat across the Gulf of Mexico waters north of 25°N and from 200 to 2600 m in depth. This study is being conducted by LGL Ecological Research Associates, Inc. (LGL) in cooperation with Texas A&M University (TAMU). The first year of the program has been completed and is reported herein.

PROGRAM OBJECTIVES

The overall objectives of the program are:

(1) To determine the abundance, structure, and distribution of animal communities in the deep sea in the Gulf of Mexico.
(2) To determine the hydrographic structure of the water column and bottom conditions at selected sites within the study area.
(3) To determine and compare sedimentary characteristics at selected sites within the study area.
(4) To relate differences in biological communities to hydrographic, sedimentary, and geographic variables.
(5) To assess seasonal changes in deep sea biological communities in terms of abundance, structure, animal size, and reproductive state.
(6) To measure present levels of hydrocarbon contamination in the deep-sea sediments and selected animals prior to, and

in anticipation of, petroleum resource development beyond the shelf-slope break.

(7) To compare the biological and non-biological characteristics of the deep Gulf of Mexico with that of other temperate and subtropical deep-sea regions.

(8) To assemble together and synthesize appropriate published and unpublished data with the results of this study, summarizing on a seasonal and spatial basis all biological, habitat, and other environmental observations and parameters.

(9) To conduct an effective quality assurance and quality control program which insures that all data acquired are accurate and repeatable within standards normally required for each type of observation, measurement, or determination.

(10) To critically review, interpret, and analyze all observations and data acquired to redefine as necessary the research program in such a way as to avoid or minimize redundancy and to optimize the efficiency of all field, labortory, and data management operations for future deep-sea studies sponsored by MMS in the Gulf of Mexico.

(11) To assess the need for and determine the type of studies to be conducted in future program efforts.

The data for meeting these objectives have been gathered on five cruises of which two were conducted during this first year of the program.

STUDY AREA AND METHODS

During Year One, three transects of five stations each were sampled, with one transect located in each of the Western, Central, and Eastern Gulf of Mexico Lease Planning Areas (Fig. 1). Average sampling depths along each transect were 348, 657, 839, 1341, and 2530 m which corresponded to the approximate bathymetric centers of previously hypothesized faunal zones: Shelf/Slope Transition (150-450 m);

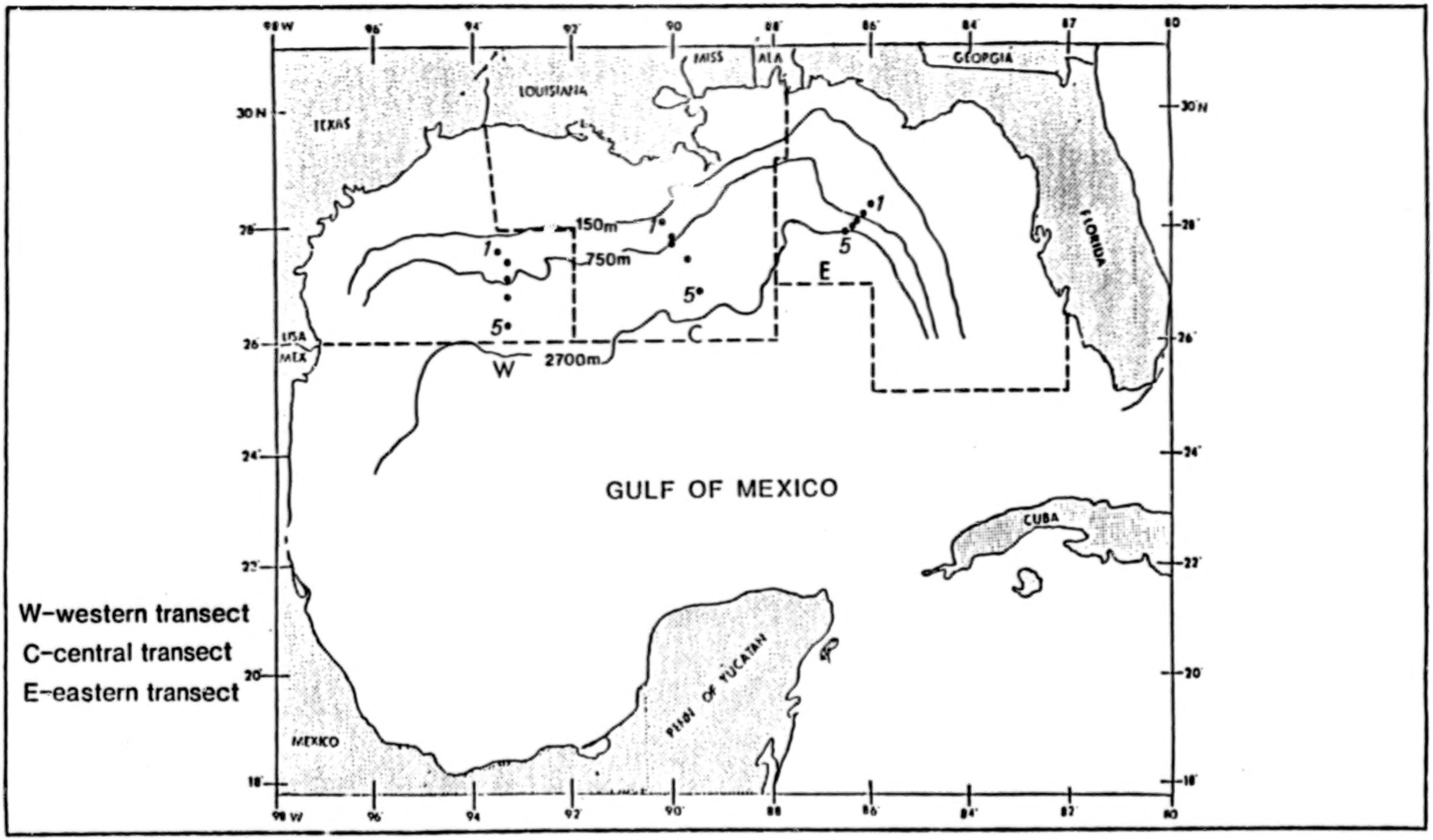

Figure 1. Location of transects and stations, within Western (W), Central (C) and Eastern (E) Gulf of Mexico lease planning areas.

Archibenthal, Horizon A (475-750 m); Archibenthal, Horizon B (775-950 m); the Upper Abyssal (975-2250); and the Mesoabyssal, Horizon C (2275-2700 m).

The types and numbers of samples taken at each station included 800 bottom photographs; a hydrocast and supportive water column sampling, either six (Central Transect) or three (East and West Transects) box cores; and a trawl sample. Box core samples were split for biological (macroinfauna, meiofauna) and physical (sediment grain size and chemistry) analyses. In November 1983, only the Central Transect was sampled whereas in April 1984, all three transects were sampled. All samples planned to be taken were obtained.

The laboratory analyses are proceeding on schedule using standard protocols for each type of physical, chemical, and biological analysis. The results which were available are reported below and in the main report volume.

ENVIRONMENTAL FEATURES

The water column over each transect was characterized by the presence of distinctive water masses (Fig. 2) that showed little seasonal or geographic variation. From top to bottom, these water masses included a shallow mixed layer of Gulf Water (usually present from the surface to 250 m); Tropical Atlantic Central Water (~300 to 500 m); Antarctic Intermediate Water (~500 to 1000 m); and Gulf Deep Water, a mixture of North Atlantic Deep and Caribbean Mid-water. The Shelf/Slope Transition Faunal Zone roughly corresponds in depth to the Tropical Atlantic Central Water mass, the Archibenthal Faunal Zone to the Antarctic Intermediate Water mass, and both the Upper Abyssal and Mesoabyssal faunal zones occur in Gulf Deep Water. Gulf Deep Water is distinctly colder than the water masses above, and temperature is undoubtably one of the important factors controlling depth distributions of organisms.

Bottom sediments at stations in the Central Transect in November 1983 (Fig. 3) were predominantly clay-sized at Stations C1, C2, and C3, with deeper stations containing higher proportions of either silt (C5) or silt- and sand-sized particles (C4). The same stations on the Central Transect during Cruise II (April 1984) typically had a higher proportion of silt-

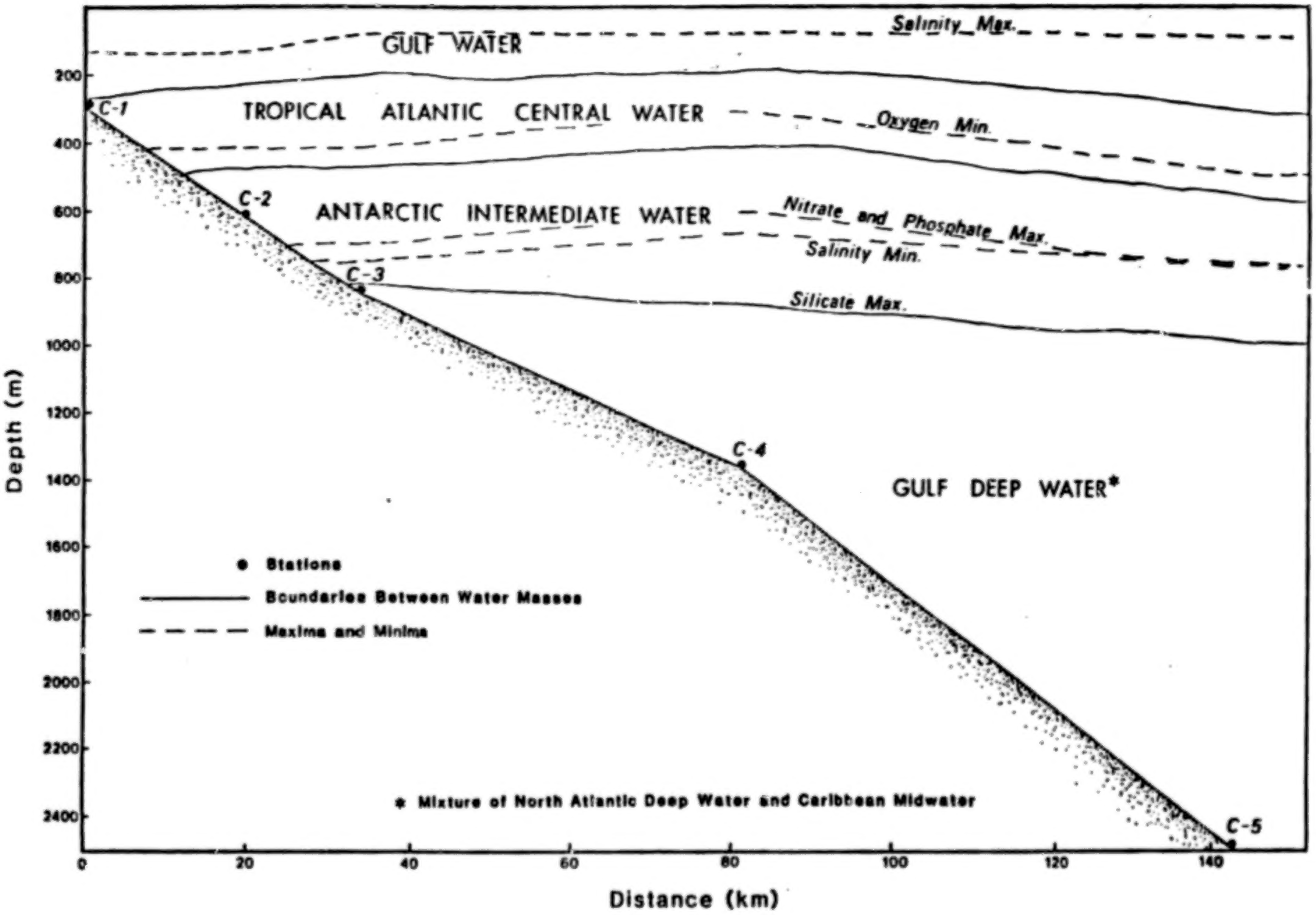

Figure 2. Water masses along the Central Transect during Cruise I. A similar distribution was observed for Cruise II.

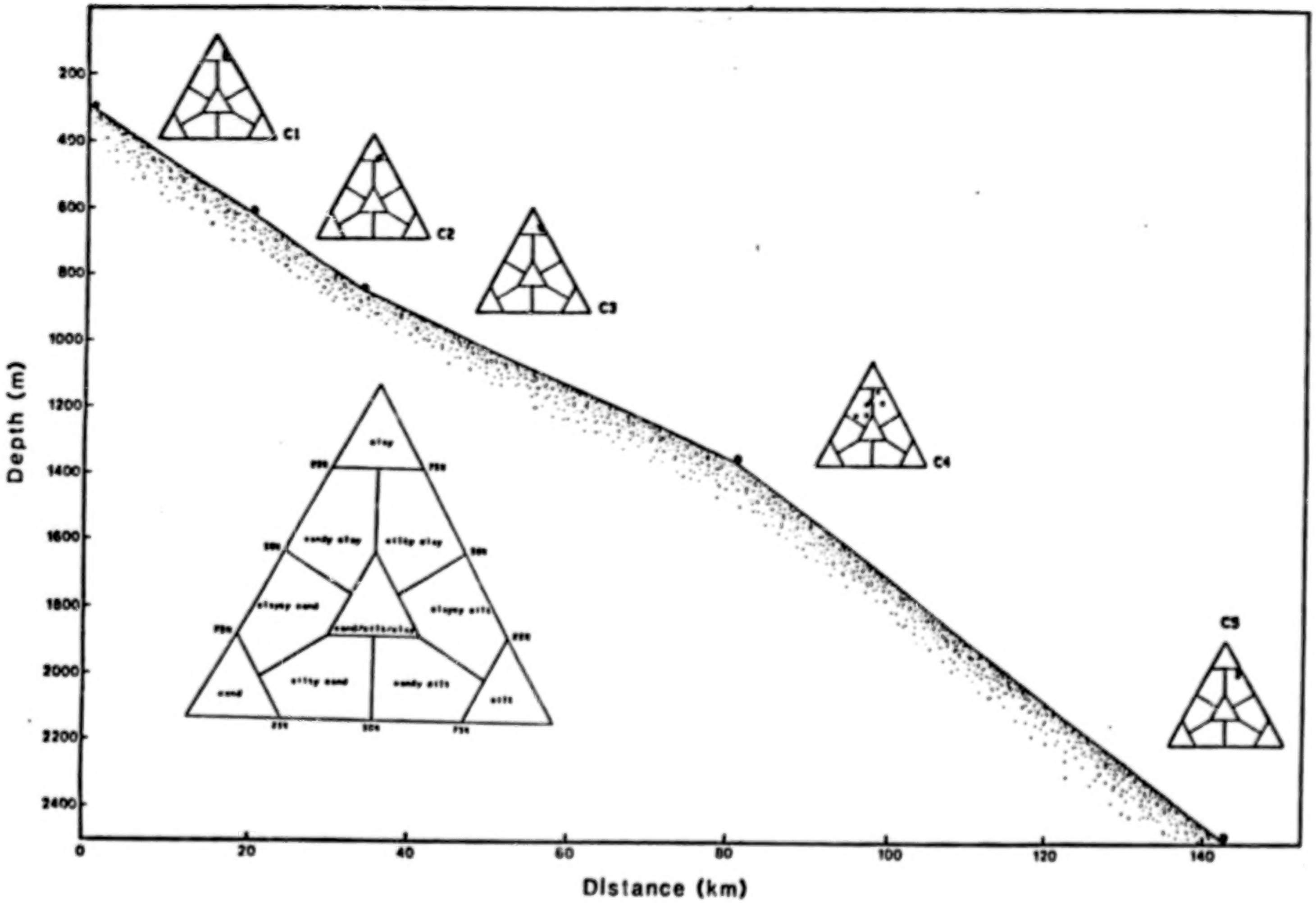

Figure 3. Sediment grain sizes at Cruise I sampling stations.

sized particles than had been observed in November of the previous fall (Fig. 3 and Fig. 4). Sediment levels of organic carbon (Fig. 5) and calcium carbonate (Fig. 6) were also higher in samples taken on Cruise II than in samples taken on Cruise I. Results of the sediment hydrocarbon levels also suggested that an influx of terrigenous material (bulk organic matter and plant biowaxes) to the bottom occurred between the two samplings.

On a geographic basis, bottom sediments at stations on the Eastern Transect contained considerably more sand and silt than sediments on the other transects, even though all stations were predominantly clay. Calcium carbonate levels were highest in sediments from the Eastern Transect, and higher in Western Transect samples than in Central Transect samples. The pattern of organic carbon levels in the sediments indicated levels to have been highest on the Central Transect, and then generally higher for sediments from the Western Transect than for sediments from the Eastern Transect. An exception was noted for the deepest station; i.e., organic carbon levels at Station E5 were higher than levels at Station W5. Organic carbon levels exhibited a trend of decrease with depth. At the Central Transect, sediment organic carbon in November 1983 was characteristic of carbon provided by marine phytoplankton, based upon carbon isotopic analyses.

With one exception, results from carbon isotopic analyses for benthic organisms not collected in the vicinity of gas seeps in April 1983 suggested that the slope biota derive their energy from sinking photosynthetic carbon (marine phytoplankton). The exception (a crab, *Geryon quinquedens*) had a carbon isotopic value suggesting a food source other than marine phytoplankton alone. Animals collected from around seeps had carbon isotope levels suggesting chemosynthesis, as opposed to photosynthesis, provided the primary production at the base of the seep-community food chain.

Sediments at all three transects had a mixture of thermogenic, terrigenous, and planktonic hydrocarbons. The two samplings at the Central Transect suggested an influx of low UCM terrigenous material occurred between Cruises I and II. This terrigenous material consisted primarily of bulk organic matter and plant biowaxes. The material being transported to this area appeared to be compositionally constant with

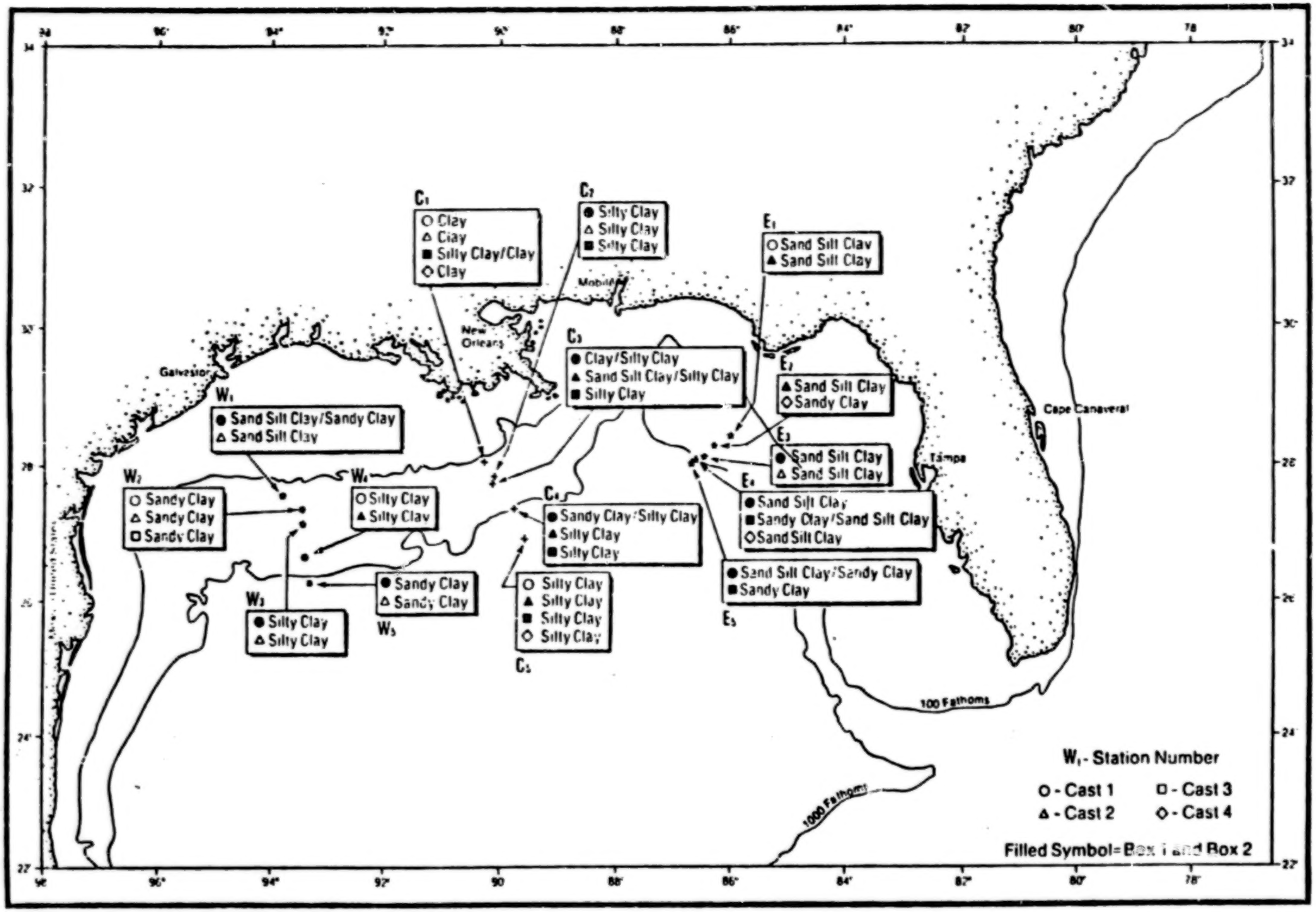
84-G-4 Grain Size

Figure 4. Grain size types (after Folk, 1974) at Cruise II stations.

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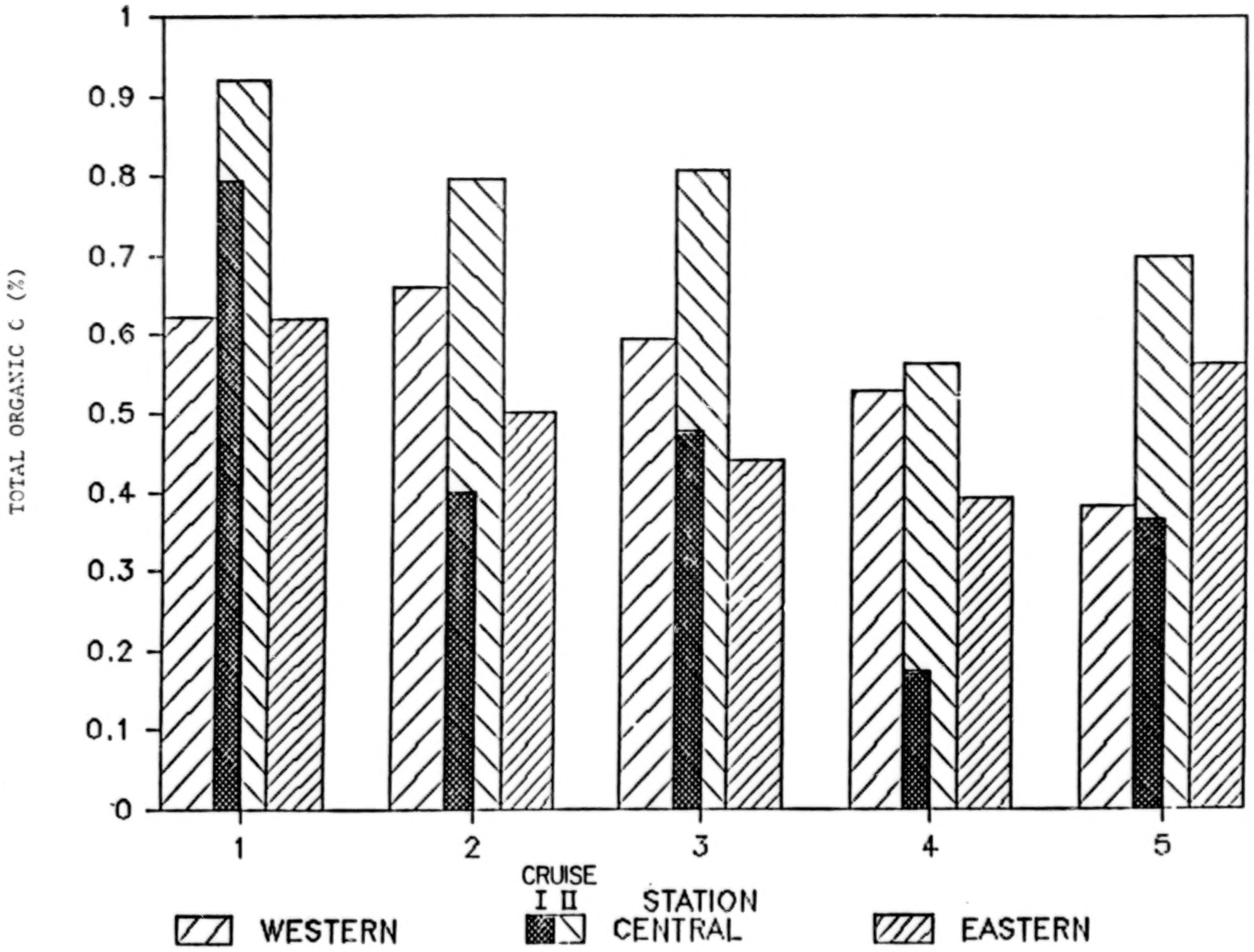

Figure 5. Average percent benthic total organic carbon for stations along the West, Central and East Transects, Cruises I and II.

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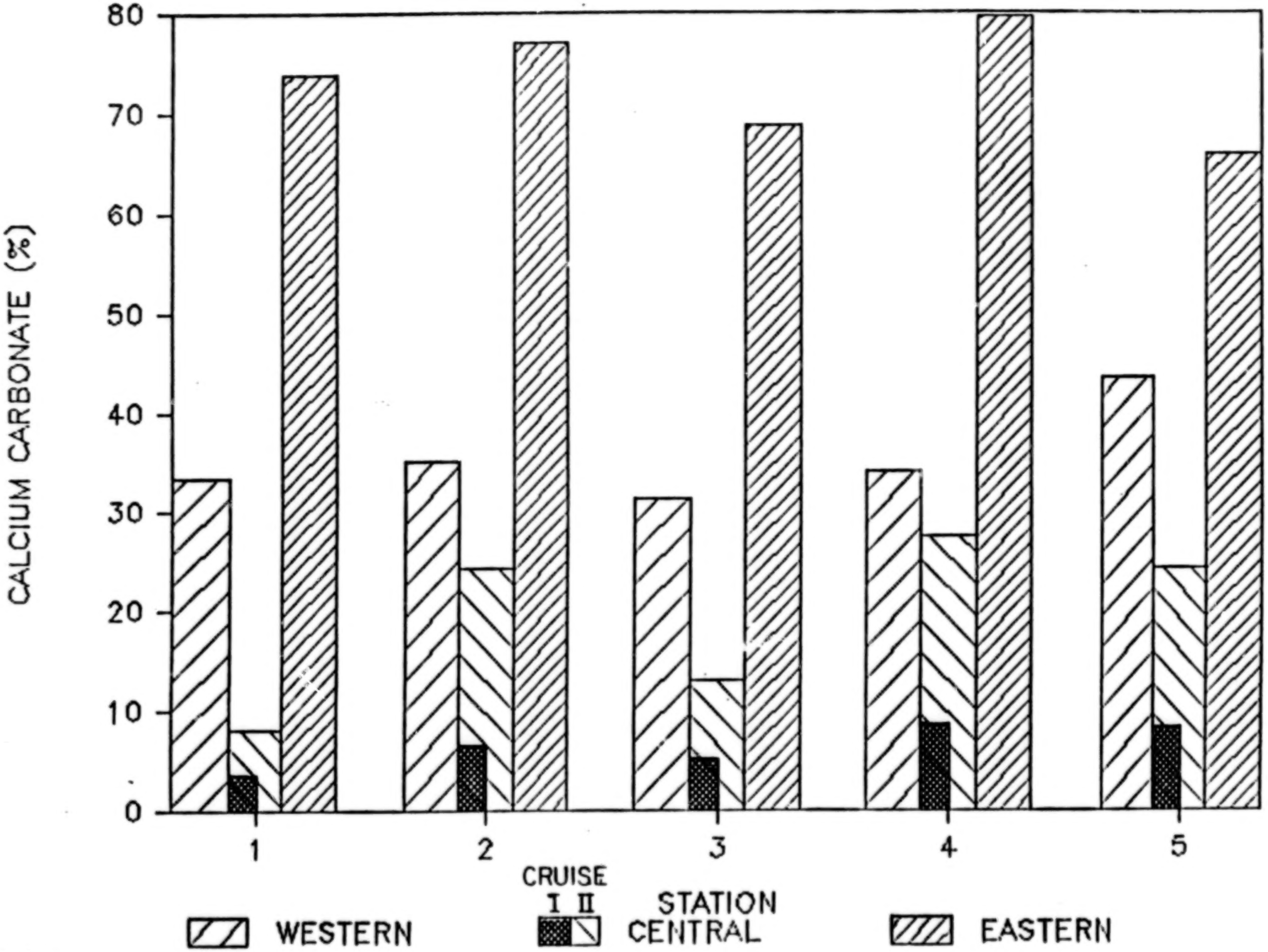

Figure 6. Average percent calcium carbonate for stations along the West, Central, and East Transects.

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time. The biowaxes were accompanied by a low molecular weight UCM and by n-C_{15} to n-C_{19} compounds. The higher molecular weight UCM appeared to accumulate in place and was much more highly degraded than the terrigenous material. Piston coring in the Gulf of Mexico intraslope has demonstrated that the Central Transect is in an area of active natural oil seepage. Piston cores sampled at these sites generally showed an increase in hydrocarbons with depth. This suggests that the source of the high molecular weight UCM in the sediments is upward migration, though transport of anthropogenic hydrocarbons to the sediment by water column particulates cannot be ruled out.

The influence of riverborne material in the sediments decreased from the Central to the West to the East Transect. The reduced hydrocarbon levels in the East Transect were primarily due to smaller terrigenous and thermogenic inputs. Planktonic and algal inputs were difficult to discern in the West and Central Transects, but were readily apparent in the East Transect as shown by the numerous alkenes detected. This may be due to more rapid sedimentation rates at the Central and West Transects and/or the large input of riverine material causing rapid dilution of oceanic detritus. Elevated microbial activity in the sediments and/or in the water column may also assist in removing the more labile marine debris.

In general, hydrocarbons were only present in low concentrations in the sediments, especially at the East Transect. Aliphatic hydrocarbon levels ranged from ~10 to 50 ppm. Aliphatic hydrocarbon levels recorded in the literature range from 1 to 3000 ppm. The low concentrations generally occur in very sandy areas, whereas the high concentrations occur in polluted, shallow waters. In areas of pervasive seepage on the Gulf of Mexico slope, aliphatic hydrocarbons have been measured in excess of 100,000 ppm.

With one exception, all organisms surveyed for hydrocarbon contamination appeared to be pristine. The exception was a pooled sample of shrimp (Nematocarcinus rotundus, five individuals) from Station E3. A complete suite of alkanes and the unresolved complex mixture present in this sample strongly suggested petroleum contamination. However, bottom tars were also collected in this trawl. The shrimp may have become contaminated in the trawl, but one would expect that contamination during sampling would have been confined to the exterior hard parts.

BIOLOGICAL FEATURES

Biological studies include investigations of the meiofauna (organisms passing through a 0.30 mm screen but retained on a 62 micron screen), the macroinfauna (organisms retained on a 0.30 mm screen) and the megafauna which were sampled by trawling. The meiofaunal collections from the Central Transect for Cruises I and II indicated a substantial increase in density occurred in April 1984 as compared to levels observed in November 1983, particularly at the shallowest station (Fig. 7). There was also a marked change in the relative abundance of major taxa, namely the increased relative abundance of Foraminifera. The density data for the Central Transect suggested a trend of decreasing abundance of meiofauna with depth.

Comparisons of the three geographic regions in terms of meiofauna density and composition showed the Central Transect to have had the highest levels as well as a higher proportion of Foraminifera than was present in collections from the other two transects (Fig. 8). Whereas the collections from the Western Transect exhibited a moderate decline in abundance with depth, no such trend was observed for samples from the Eastern Transect.

The meiofaunal collections are yielding good numbers of a newly described phylum, the Loricifera, and the poorly-known kinorhynchs. Both groups contain at least genera and species new to science. It is now known that the Loricifera are not restricted to shallow, sandy substrates, given that collections have been taken as deep as 2530 m on clay bottoms.

Density levels of macroinfauna from the slope taken during this study are markedly higher (range was from 2435 to 8628 organisms/m^2) than levels previously reported from the Gulf of Mexico slope and abyss (25 to 1095 organisms/m^2). Our samples were screened with a seive having 0.30 mm mesh whereas the previous study used a 0.42 mm mesh. The typical macroinfauna we are seeing from the samples are minute, making weighing impractical without destroying the samples. The size feature probably also accounts, in large part, for the disparity between our and previous measurements of macroinfaunal density from deep-Gulf habitats.

The seasonal data for the macroinfauna from the Central Transect also suggested an increase in density in April 1984 as compared to November

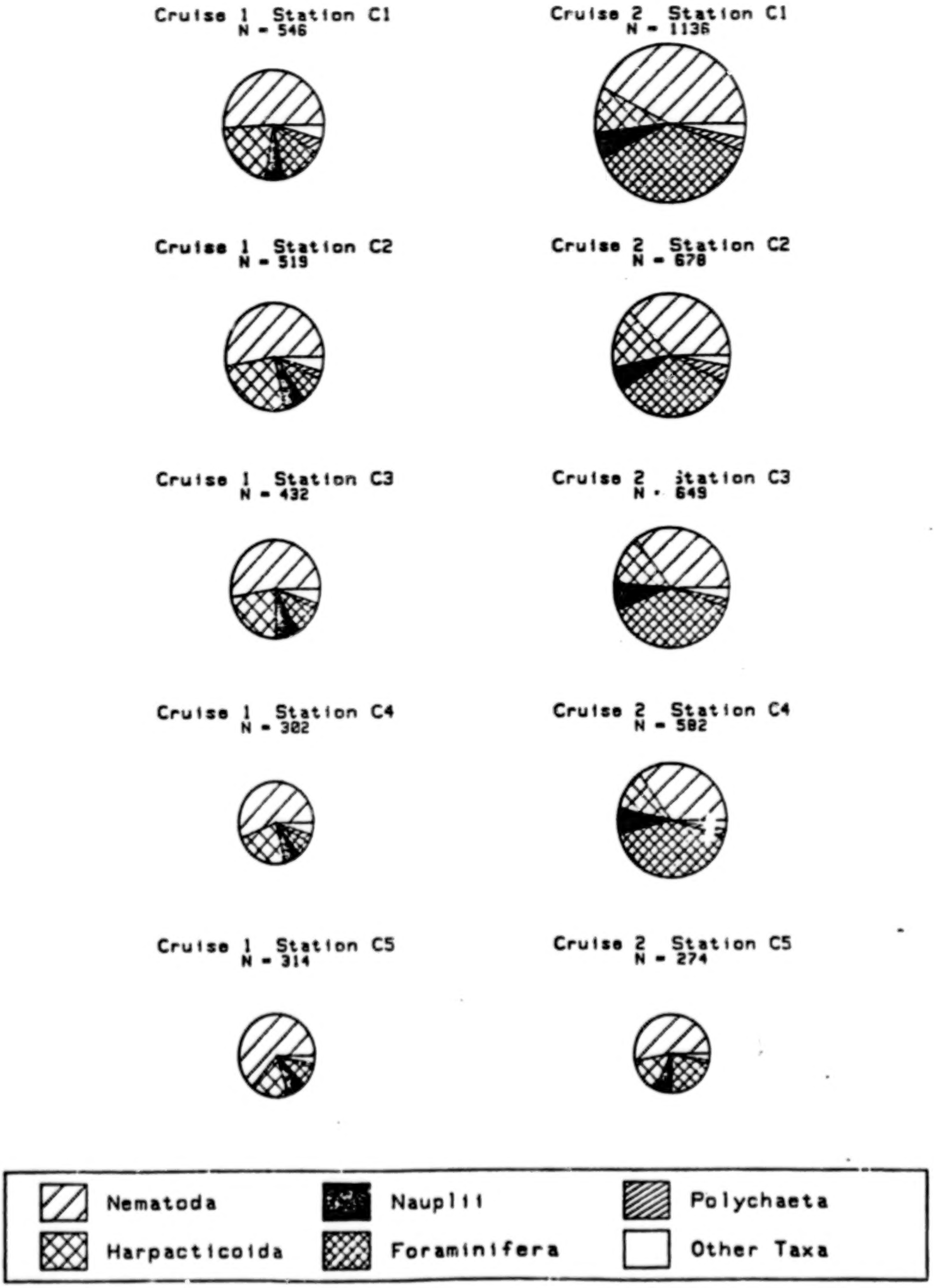

Figure 7. Comparison of meiofauna densities (no./10 cm^2) between Cruises I (November 1983) and II (April 1984) on the Central Transect. Note the large increase of forams in Cruise II diagrams. Comparisons can be made on both axes.

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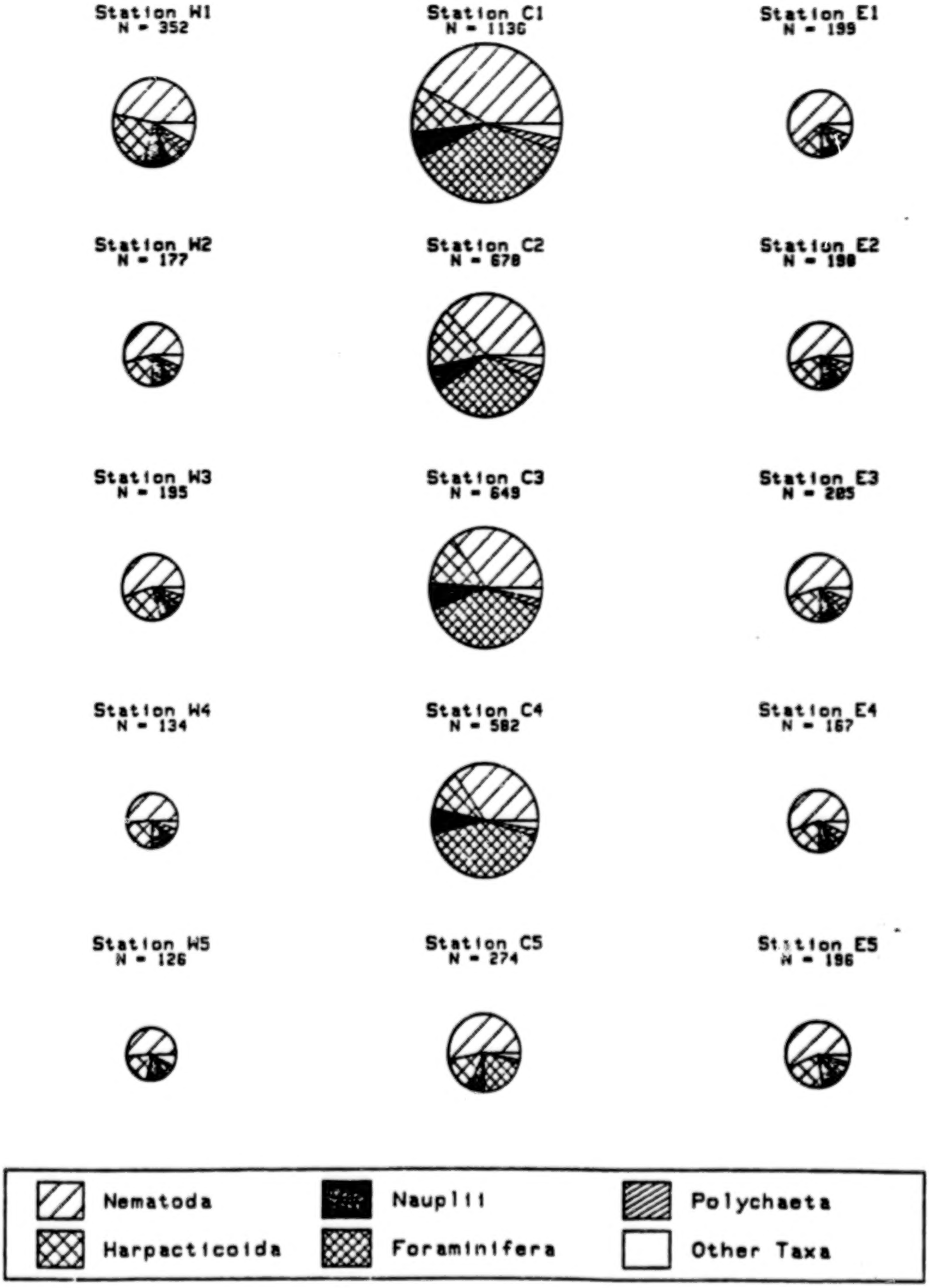

Figure 8 . Comparison of meiofauna densities (no./cm^2) obtained during Cruise II (April 1984). Comparisons can be made on both axes.

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1984, but the increase was not nearly as pronounced as the change observed for meiofauna (Fig. 9). On the Central Transect, density of macroinfauna did not exhibit a pronounced decrease with depth, but there was an obvious decline in abundance at 2530 m (Station C5). Polychaetes were the numerical dominants at all depths on the Central Transect except at 2530 m where nematodes of a macroinfaunal size equalled or exceeded the relative numbers of polychaetes.

Macroinfaunal densities on the Eastern and Central Transects were higher than the density of organisms found on the Western Transect (Fig. 10). The Western Transect also differed in that macroinfaunal density exhibited a decline with depth. On both Central and Eastern Transects, density levels were rather consistent from 348 to 1341 m, dropping sharply at 2530 m.

The macroinfaunal groups which have been sorted to the species level are exceedingly diverse and contain many new species and genera. The taxonomist for the tanaidacean collections has indicated that once all the specimens from Cruise II are described, it will increase the number of known species, world-wide, by 20%.

Of the megafauna collected to date, the decapod crustaceans, echinoderms and demersal fish collections have been identified to the species level. There were 78 species of decapods (led in variety by the anomurans, including the galatheids), 33 species of echinoderms (not including the brittle stars) and 94 species of fish representing 42 families. Bathymetric distributional patterns of the megafauna collected to date agree very closely with previous work, providing credence to historical faunal zonation and assemblage characterization schemes based upon the megafauna.

The benthic photography aspect of the program to date has been mainly devoted to the development of quantitative analytical procedures which have now been finalized. Preliminary results of photographic analysis for Stations W1, C1, and E1 from Cruise II indicate Station C1 was characterized by a greater density of both biota and Lebensspuren than the other two stations.

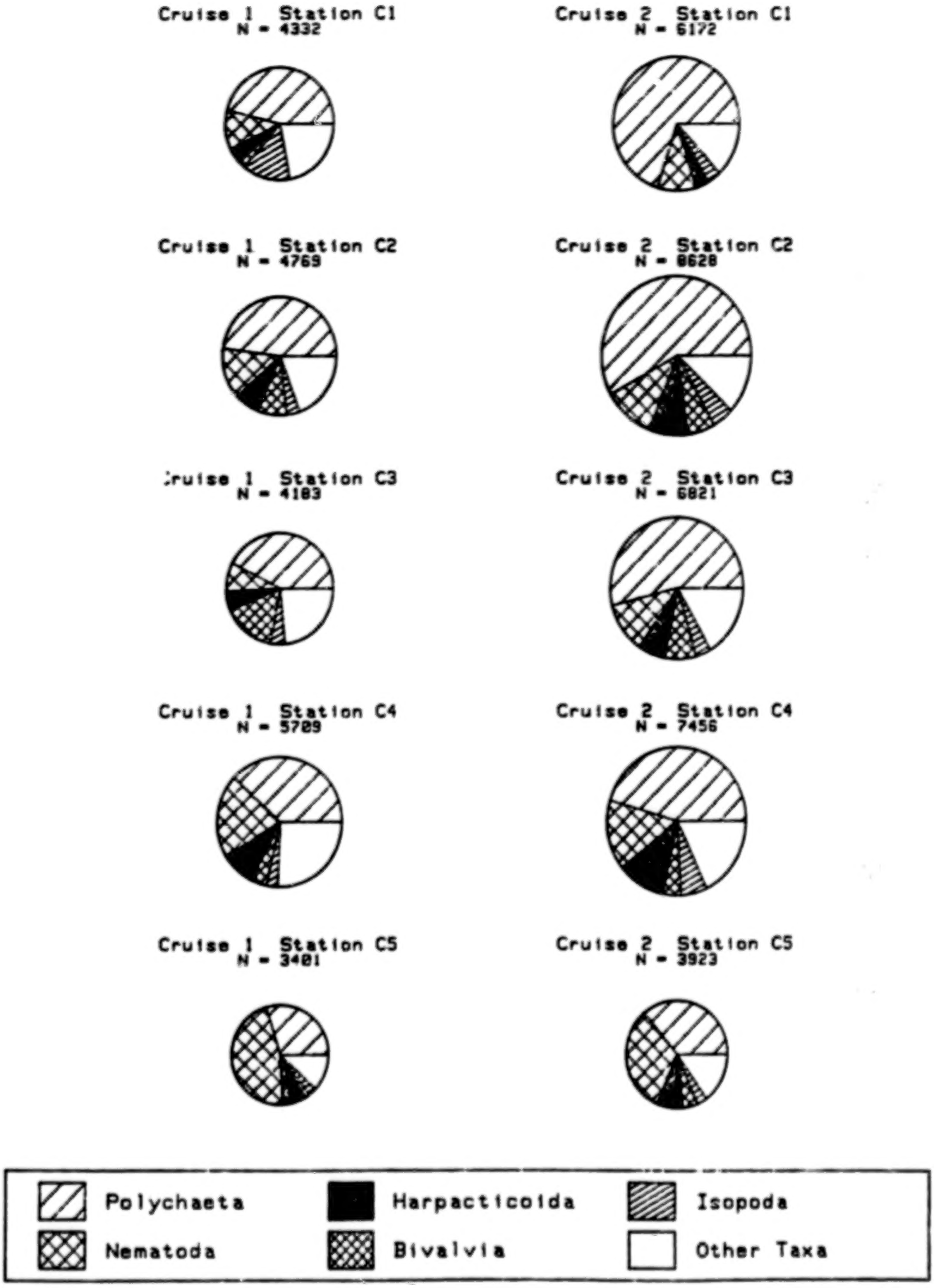

Figure 9. Comparison of macroinfauna densities (no./m^2) between Cruise I (November 1983) and Cruise II (April 1984) stations.

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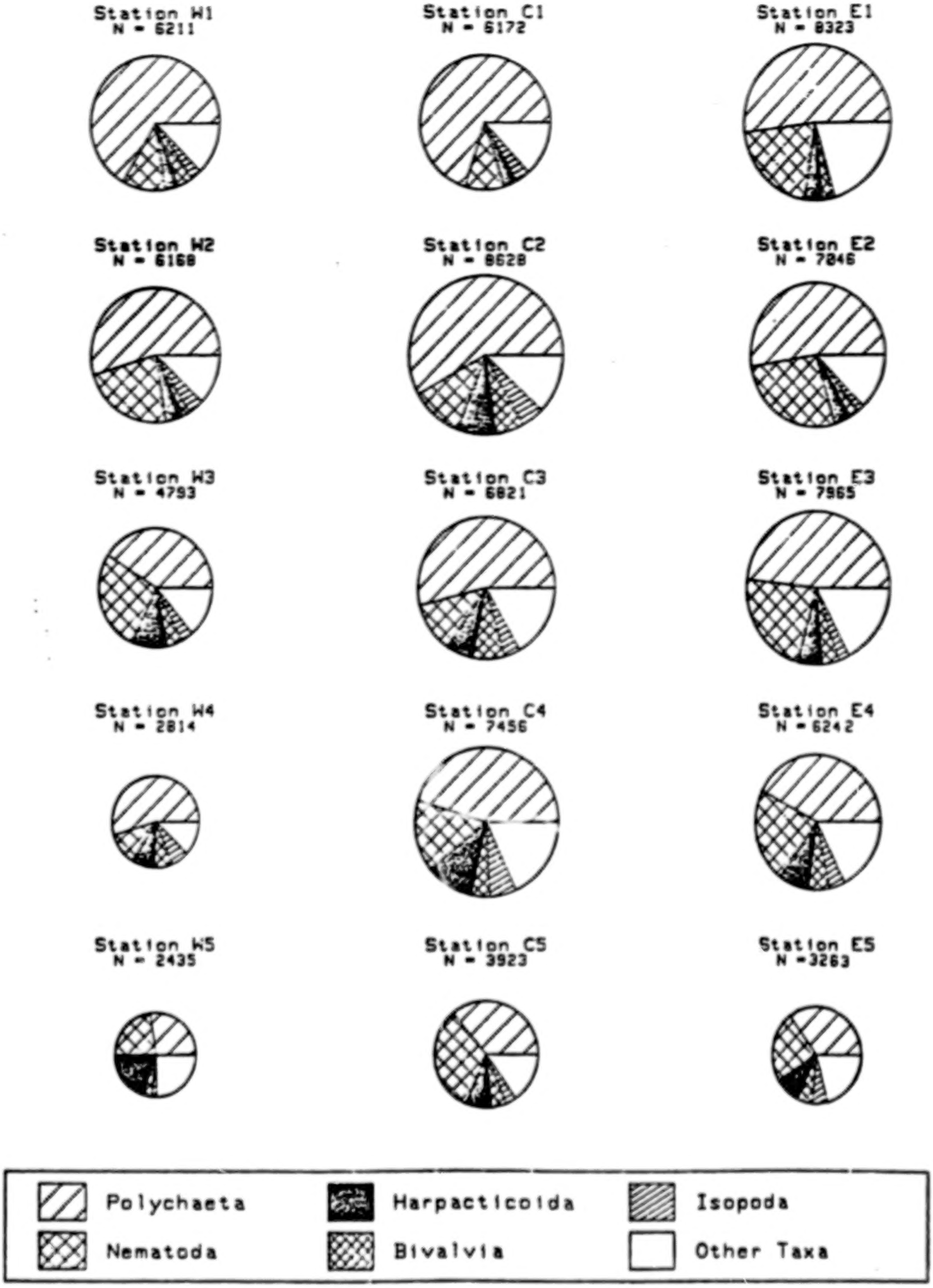

Figure 10 . Comparison of macroinfaunal densities (no./m^2) obtained during Cruise II (April 1984).

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CONCLUSIONS

Few conclusions can, or should, be made at this early point in the program. However, it would appear that there are marked regional differences in the slope environment and biota, as well as seasonal changes. The latter may prove to be related, in large part, to the influence of river discharge.

From the standpoint of hydrocarbon contamination, the slope environment and biota have thus far appeared pristine, or nearly so. Natural seeps are prevalent in the vicinity of the Central Transect and may, in fact, provide an additional source of energy to newly discovered chemosynthetic communities in this region. Data from Cruise III suggest this to be the case. The results of that cruise will be described in subsequent reports.

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OCS STUDY
MMS 85-0046

A NUMERICAL MUD DISCHARGE PLUME MODEL FOR OFFSHORE DRILLING OPERATIONS

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OCS STUDY
MMS 85-0046

A NUMERICAL MUD DISCHARGE PLUME MODEL FOR OFFSHORE DRILLING OPERATIONS

by

Roger Multer

Hydraulics Laboratory
U.S. Army Engineer Waterways Experiment Station
P.O. Box 631
Vicksburg, Mississippi 39180

Prepared under Contract 14-12-0001-30012

for

Minerals Management Service
Gulf of Mexico OCS **Regional** Office
New Orleans, Louisiana 70123

July 1985

III

REPORT AVAILABILITY

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This volume should be cited as:

Multer, R. 1985. A Numerical Mud Discharge Plume Model for Offshore Drilling Operations. (Final Report by U.S. Army Corps of Engineers submitted to the Minerals Management Service, New Orleans, LA. Contract No. 14-12-0001-30012). 16 pp.

ABSTRACT

This study involved the modification and subsequent application of a generic plume model developed by the Walden Division of Abcor Inc. under contract to the US Army Corps of Engineers. The mathematical basis of the model is a unidirectional, steady, Reynolds type diffusion equation. To close the governing equation, coefficients of eddy diffusion are introduced and a hypothesis of similar mass and momentum diffusion invoked to define them. Also made is an assumption that the velocity may be replaced by its mean over the depth. This substitution facilitates separation of the original equation into two partial differential equations. One equation models the effect of lateral diffusion and is solved analytically. The other models the interaction of settling, longitudinal transport, and vertical diffusion and is solved numerically. The effect of this separation of variables is a substantial reduction in the computational labor.

As a part of the study a new computer program was written to perform the numerical computations. The reasons for this were

1) The original model only allowed for initial, upstream distributions which were uniform over the depth. The new model allows for inflow of the material through a "window" which begins at some elevation at or above the bottom and ends at or below the free-surface.
2) The original model required that the distribution of material at the upstream boundary be specified as concentration. The revised model allows either concentration or mass flux to be used.
3) The original model used (apparently) a general library subroutine for solving systems of numerical equations. It was desired to have a version of the program which could be used reasonably on much slower microcomputers. Therefore, a semi-implicit, tridiagonal algorithm was introduced to make the computations highly efficient.
4) Output tables not generated by the original model were desired and code appropriate for generating these was added. Principal among these is a table which gives the rate of deposition.

A second program which sets up the data needed by the numerical computation program was also written. This program asks the modeler a series of questions and stores the responses in a data file which is subsequently used by the numerical plume model. The combination of the two programs form an interactive, easy to use, tool for studying mud plumes.

PREFACE

The study reported herein was conducted during the period March 1983 to August 1984 by the Hydraulics Laboratory of the US Army Engineers Waterways Experiment Station (WES) under the general supervision of Messrs. H. B. Simmons and F. A. Herrmann, Jr., Chiefs of the Hydraulics Laboratory, and M. B. Boyd, Chief of the Hydraulic Analysis Division. The study was sponsored by the Mineral Management Service (MMS) of the Department of Interior under Requisition Numbers 3-6036-0010 and 3-6036-0046, and Contract Number 14-12-001-30012.

Dr. B. H. Johnson was project manager for the study. Dr. R. H. Multer developed the computer code and conducted the numerical study. Commander and Director of WES during the period of this study was COL Tilford C. Creel, CE Technical Director was Mr. Fred R. Brown.

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FIGURE 1

APPENDIX A: PROGRAM LISTING OF PLUME MODEL A1

APPENDIX B: PROGRAM LISTING OF FRNT B1

PART I: INTRODUCTION

1. The study which is described in this report involved the modification of a generic plume model to compute the dispersion of material discharged in off-shore drilling operations. The original model was developed by B. A. Wechsler and D. A. Cogley* under contract to the Corps of Engineers as a part of the Dredged Material Research Program. The model assumes that the velocity field is time-invariant and constant in magnitude and direction. The depth of the fluid is also constant. The planer region occupied by the fluid is assumed to be a half-plane. This latter assumption is consistent with the environment of off-shore drilling rigs which are usually far from shoreline boundaries.

The objectives of the study were:

a. Make the model more flexible so that cases where the initial distribution of sediment varied with respect to depth could be considered.

b. Incorporate a nonconstant definition of eddy diffusion into the model.

c. Incorporate an algorithm into the model to compute the total sediment flux at various downstream distances.

d. Incorporate an algorithm into the model to compute the rate of deposition.

e. Adapt the model for execution on small micro- or mini-computers.

These are in essence the tasks which were accomplished. Relative to item (e), an examination of the model was made in terms of its numerical efficiency. It was determined that the efficiency of the computations could be much improved by taking advantage of the fact that the system of equations to be solved was tridiagonal and stationary so that the equation needed to be solved only once instead of for each progressive step downstream from the injection point.

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* Wechsler, B. A. and Cogley, D. R., "A Laboratory Study of the Turbidity Generation Potential of Sediments to be Dredged," WES Technical Report D-77-14, November 1977.

2. Emperical relations are required to close the analytical description of a turbulent plume. Wechsler and Cogley use an algebraic closure which is not unreasonable, although, conversely it is not necessarily correct. Pursuit of this point is beyond the scope of the current investigation.

PART II: DESCRIPTION OF THE MODEL

Basic Equations

3. The basic equation to be solved is the steady state three-dimensional transport-diffusion equation. Assuming eddy diffusion, this equation can be written as:

$$\underbrace{\frac{\partial}{\partial x}(uc)}_{\text{downstream advection}} + \underbrace{\frac{\partial}{\partial v} \int wf(w)dw}_{\text{vertical sedimentation}} \underset{\text{eddy diffusion}}{\underline{- \frac{\partial}{\partial x}\left(E_x \frac{\partial c}{\partial x}\right) - \frac{\partial}{\partial y}\left(E_y \frac{\partial c}{\partial y}\right) - \frac{\partial}{\partial z}\left(E_z \frac{\partial c}{\partial z}\right)}} = 0 \qquad (1)$$

where

x = downstream coordinate

y = vertical coordinate

z = lateral coordinate

u = current velocity at any point

c = sediment concentration

w = settling velocity

f(w) = settling-velocity frequency distribution

E_x, E_y, E_z = eddy diffusivities in x, y, and z directions

4. This equation is based on the assumptions that the flow is steady, uniform, and fully turbulent, and that eddy diffusion can be characterized by Fick's law with eddy diffusion coefficients. Equation 1 is unclosed and several assumptions were made by Cogley and Wechsler in order to simplify its solution. These are:

a. Eddy diffusion in the downstream direction is negligible compared to the other two diffusive transport terms.

b. The flow is fully turbulent, therefore, the local velocity u in Equation 1 can be replaced by the mean velocity U.

c. The mass and momentum diffusion coefficients in the vertical direction are essentially the same.

d. The shear stress is linearly distributed over the depth, and the velocity distribution is given by Von Karman's "universal" distribution.

e. The lateral eddy diffusion coefficient is essentially constant over the depth.

5. Based on the above assumptions, algebraic expressions for E_y and E_z can be written as:

$$E_y = 0.4\ U\ y(1 - y/h)\ \mathrm{sqrt}(f/8) \tag{2}$$

and

$$E_z = 0.2\ h\ U\ \mathrm{sqrt}(f/8) \tag{3}$$

where f is the Darcy friction factor and U is the depth averaged current velocity. For each fraction of the sediment load for which the settling velocity is constant, Equation 1 may be rewritten as:

$$U \frac{\partial C}{\partial x} + w \frac{\partial C}{\partial y} - \frac{\partial}{\partial y} E_y \frac{\partial C}{\partial y} - \frac{\partial}{\partial z} E_z \frac{\partial C}{\partial z} = 0 \ , \tag{4}$$

which together with Equations 2 and 3 is the model of the process considered here.

Boundary Conditions

6. Physically, the boundary condition for the free surface must specify that there is no flux across the free surface. This condition is described mathematically by:

$$E_y \frac{\partial C}{\partial y} + wC = 0 \tag{5}$$

Cogley and Wechsler assume that all of the sediment reaching the bottom is deposited and that there is no reentrainment. The corresponding boundary condition is:

$$E_y \frac{\partial C}{\partial y} = 0 \tag{6}$$

Separation of Variables

7. It may be assumed that the solution for Equation 4 is of the form:

$$C(x,y,z) = C_o(x,y)\; C_d(x,z) \tag{7}$$

On substituting Equation 7 into Equation 4 the following two equations are obtained:

$$U \frac{\partial C_o}{\partial x} + w \frac{\partial C_o}{\partial y} = \frac{\partial}{\partial y}\left(E_y \frac{\partial C_o}{\partial y}\right) \tag{8}$$

and

$$U \frac{\partial C_d}{\partial x} = \frac{\partial}{\partial z}\left(E_z \frac{\partial C_d}{\partial z}\right) \tag{9}$$

Or, stated another way, if C_o and C_d are solutions of Equations 8 and 9, respectively, their product is a solution of Equation 4. A solution of Equation 9, which is applicable to situations where there are no lateral constraints on the flow is:

$$C_d(x,z) = {\frac{4\pi x E_z}{U}}^{-1/2} \int_{-b}^{b} \exp\left(- \frac{(z-v)^2 u}{4xE_z}\right) dv \tag{10}$$

Equation 8 is a mathematical description of a two-dimensional diffusion process in which there is no lateral diffusion. It must be solved numerically.

8. The plume's suspended sediment concentration i.e. the solution given by Equation 7, is symmetric about the x-axis and the maximum concentration occurs at the centerline. Equation 9 models the distribution of the sediment in the lateral direction. The quantity C_d (x,0) is then in effect a description of the centerline dilution which results from lateral diffusion.

9. In concluding this section it seems pertinent to observe that Equation 4 is homogenous which means that if C(x,y,z) is some solution then so is aC(x,y,z) where a is any constant. The consequence of this homogenuity is that C has no particular dimensions associated with it. The convention which has been adopted is to specify distances in meters, velocities in meters/sec, and concentration in grams per cubic meter (equal to milligrams per liter). It follows that mass fluxes have the dimensions of grams/sec and that rates of deposition have the dimensions of grams/sec per square-meter.

Numerical Approximations

10. **A numerical approximation** of Equation 8 may be developed on a Cartesian grid. The approximation employed in this study is explained briefly in this section. Equation 8 may be rewritten as:

$$\frac{\partial}{\partial y}\left(E_y \frac{\partial C_o}{\partial y}\right) = U \frac{\partial C_o}{\partial z} + w \frac{\partial C_o}{\partial y} \tag{11}$$

Suppose first that there is no diffusion. The equation corresponding to this case is:

$$U \frac{\partial C_o}{\partial x} + w \frac{\partial C_o}{\partial y} = 0 \tag{12}$$

and it has the solution:

$$C_o(x,y) = f\left(y - \frac{w}{U} x\right) \tag{13}$$

The Cartesian grid (see Figure 1) may be defined by the generators $\{x(i+1) = x(i) + dx\}$ and $\{y(j+1) = y(j) + dy\}$ in which case (i,j) represents a unique grid point. According to Equation 13, C_o is constant along the line with slope w/U which passes thru the point (i,j). This line will intersect the vertical line $x(i-1)$ at an elevation of $y(j) - w/U\ dx$. Assuming that C_o is known at the set of points $\{i-1,\ j = 0,1,2,\ldots.\}$ and that w/U is less than dy/dx, C_o may be estimated by interpolating linearly between the points $(i-1,j)$ and $(i-1,j+1)$. The equation for this is:

$$C_o(i,j) = \frac{\left(dy + \frac{w}{U} dx\right)}{dy} C_o(i-1,j) - \frac{w}{U} \frac{dx}{dy} C_o(i-1,j+1) \tag{14}$$

Equation 14 is used as a replacement for the right hand side of Equation 11.

11. Using a Taylor series expansion it may be shown that to an order of dy squared:

$$\begin{aligned} \frac{\partial}{\partial y}\, E_y \frac{\partial C}{\partial y} = {} & (E_y(j+1)+E_y(j))/(2*dy*dy)*C_o(i,j+1) \\ & + (E_y(j)+E_y(j-1))/(2*dy*dy)*C_o(i,j-1) \\ & - (E_y(j+1)+2*E_y(j)+E_y(j-1))/(2*dy*dy)*C_o(i,j) \end{aligned} \tag{15}$$

This relationship is used as a replacement for the left hand side of Equation 11 in the numerical approximation.

12. The result of substituting Equations 14 and 15 into Equation 11 is a system of linear equations for each i. Examining Equation 15, it can be seen that the system of equations is tridiagonal and furthermore that the system is independent of i, i.e., x. These factors influence the time required to accomplish the computation since the system of equations need be solved only once. Also, while in general a computation of order n cubed is required to solve n linear equations, the computation required to solve a tridiagonal system is only of order $3n$.

PART III: APPLICATION OF THE MODEL

Model Input

13. The input quantities which must be specified are the depth h , the mean current velocity U , the Darcy friction factor f , and a description of the sediment and the manner in which it enters the flow. The sediment is regarded as consisting of a finite sum of parts or fractions, and the fall velocity for each fraction must be specified. The sediment enters the water column through an imaginary or virtual window (see Figure 1). The modeler, having specified the depth, h , specifies the number of stations in the y or vertical direction, Nys. Station Number 1 is at the bottom and the station Nys is at the free surface. The distance between stations in the vertical direction is

$$dh = h/(Nys - 1) \tag{16}$$

The bottom and top of the window are specified in terms of station numbers. For example, if

h = 50 meters

and

Nys = 21

then

dh = 50/20 = 2.5 meters

and if the bottom of the window is specified as vertical station 10 and the top of the window is specified as station 15 then

elevation of window bottom = 10*2.5 = 25 meters

and

elevation of top of window = 15*2.5 = 37.5 meters

Sediment inflow into the model may be specified in terms of either a mass concentration (mass/volume) or as a mass flux (mass/time).

14. Other quantities which the modeler must specify are the number of stations in the longitudinal direction, Nxs, and the distance, delx, between them; as well as, the number of stations in the lateral direction, Nzs, and the lateral distance between then, delz. These parameters may be selected as the modeler chooses, and in many cases the modeler may elect to make several runs with different selections of delx and delz.

15. Data for the model is setup by a program called FRNT. On typing the command FRNT into the microcomputer, the system responds with a series of questions:

```
STREAM VELOCITY (M/SEC) = ?
DEPTH IN METERS = ?
FRICTION FACTOR (RANGE = 0.005 TO 0.025) = ?
LONGITUDINAL DISTANCE BETWEEN STATIONS IN METERS = ?
LATERAL DIST. BETWEEN STATIONS IN METERS = ?
NUMBER OF STATIONS IN LONGITUDINAL DIRECTION = ?
NUMBER OF STATIONS IN THE VERTICAL DIRECTION = ?
NUMBER OF STATIONS IN THE LATERAL DIRECTION = ?
WIDTH OF INFLOW WINDOW (METERS) = ?
STATION NUMBER FOR BOTTOM OF WINDOW (1 IS BOTTOM) = ?
STATION NUMBER FOR TOP OF WINDOW (≤ NUMBER OF Ys) = ?
MASS FLUX OR CONC. BOUNDARY CONDITION ( M OR C) = ?

    if response = M

    then:

MASS FLUX (IN UNITS OF GRAMS/SEC) = ?

    else if response = C

    then:

CONCENTRATION (GRAMS/LITER) = ?
NUMBER OF SIZE FRACTIONS (1 to 9) = ?
% OF MASS FOR FRACTION 1 ( 0 TO 100) = ?
SETTLING VELOCITY FOR FRACTION 1 (CM/SEC) = ?

    repeat until data is obtained for the number of fractions specified.
```

Each of the questions is answered by inputting the appropriate information followed by a carriage return. FRNT generates a file called PLUME.VRS (plume-variables). This file looks like:

```
 1.  U            =        0.05
 2.  H            =         100
 3.  FF           =        0.01
 4.  DELX         =        1000
 5.  DELZ         =         100
 6.  NXS          =          41
 7.  NYS          =           5
 8.  NZS          =           5
 9.  2*BO         =          50
10.  WBOT         =           3
11.  WTOP         =           4
12.  OPT          =           M
13.  FLUX         =      100000
14.  NFACS        =           1
15.  PCTMF        =         100
16.  V            =           0
```

Entries in the last column are responses which the modeler gave to FRNT. The order of these entries is the same as that of the questions which FRNT asks. The file PLUME.VRS may be edited, copied to the printer, etc. In editing the file, the last column must be properly right justified.

Running the Model

16. To run the plume model, the modeler simply types in MODEL. The computer will first output the relevant input variables to the printer, and then respond with a series of questions which are as follows:

```
PRINT TABLE OF MASS FLUXS (Y OR N)?
PRINT SUM OF CO TABLE (Y OR N)?
PRINT TABLE OF CD VALUES (Y OR N)?
PRINT CONCENTRATION TABLE (Y OR N)?

To generate a table of concentrations

ENTER THE DEPTH AT WHICH CONCENTRATION IS WANTED

To stop generating concentration tables

ENTER A NEGATIVE NUMBER
(DEPTHS ARE ROUNDED TO THE NEAREST NODAL EVALUATION)

PRINT TABEL OF DEPOSITION RATES (Y OR N)?
```

The tables corresponding to the second and third questions are the solutions (if one fraction is specified) of Equations 8 and 9 respectively. If more than 1 fraction is specified, the second table is the solution of Equation 8 summed over all of the fractions. The table corresponding to the first question gives the total mass flux and the mass flux for the various fractions across planes normal to the x-axis at various downstream locations. Concentrations at various depths are generated in response to the fourth query, and as many of these tables as are desired may be generated. Entry of a negative number halts the generation of these tables. The last table which may be generated is a table of deposition rates. This table gives deposition rates as mass per unit area per unit time.

Special Considerations

17. Referring back to Equation 13 in which vertical diffusion is ignored, observe that in the time it takes a particle to advance a distance dx, the distance between two stations in the longitudinal direction, it will fall

a distance

$$dy = w/U \, dx \quad (17)$$

Equation 14 uses two succesive grid elevations under the assumption that the characteristic line

$$y = w\,x \,/\, U \quad (18)$$

falls in the interval $y(j)$ to $y(j+1)$. This will happen only if the distance dh between two vertical stations is greater than or equal to dy . The inequality consistent with the assumption is

$$dh > dy = w/U \, dx \quad (19)$$

If this inequality is violated the numerical solution of Equation 8 becomes unstable (wild unpredictable numerical output is generated). Since the depth h , the settling velocity w , and the mean current velocity are fixed, and since

$$dh = h \,/\, (Nys-1) \,, \quad (20)$$

where Nys is the number of stations in the vertical direction, Equation 19 imposes a restriction on the values of dx and Nys which may be used. The most restrictive case in a given situation will be for the material with the greatest settling velocity. The computer checks the inequality and when it is not satisfied prints the message

```
Dy/Dx MUST BE > OR = w/U FOR STABILITY
w/U = .........  DELY/DELX = .........
DECREASE DELX OR NYS ... COMPUTATION ABORTED
```

In a number of instances it has been found desirable to run the model first with a relatively small dx until the sand fraction settles out. After removing the sand fraction from the distribution the model is rerun with a correspondingly larger dx value.

18. Suppose that there is one fraction with zero settling velocity. Material must be conserved within the flow and the mass flux across any section normal to the x-axis will be

$$\text{mass-flux} = (2boh)\ \text{avg}(C_o)U \quad (21)$$

This equation is satisfied by the numerical model if the equation

$$\mathrm{avg}(C_o) = \sum_{n=2}^{Nvs-1} C_n \tag{22}$$

is used to compute the average of C_o. In many instances it is the mass flux and not the initial concentration which is known. The numerical model uses Equations 21 and 22 to compute the upstream concentration when the mass flux is given. Using the divergence theorem it is not difficult to show that the mass flux per unit area across a horizontal surface is

$$q = wC + E_y \frac{\partial c}{\partial y} \tag{23}$$

At the bottom the boundary condition is

$$\partial C/\partial y = 0 \tag{24}$$

Hence, the rate of deposition is just

$$q = wC \tag{25}$$

PART IV: SUMMARY AND CONCLUSIONS

Summary

19. The plume model developed in this study incorporates the major physical mechanisms which influence the behavior of a suspended material. However, the model is still simple enough to be run on relatively small computers. The model does, however, have limited applicability because of the many assumptions made, e.g. the current is considered independent of time and is constant in magnitude and direction.

20. The model has been run on both 8 bit micro and 32 bit super microcomputers. The modeling system consists of two programs, FRNT which sets the problem up, and MODEL which performs the actual computations. Both of the programs are interactive and use a question and response mechanism to communicate with the user. Variables such as the current velocity are fixed by physical circumstances while other variables such as the number of stations in the x , y , and z directions are free for the modeler to choose. The only restriction on the choice of these variables is the stability criterion indicated in PART III of this report. The computer code (MODEL) checks Equation 19 and aborts the run if the criterion is not met.

21. A number of runs have been made in testing the model. The coarsest material (and the size of the computer memory) limit the longitudinal distance which can be modeled because of the stability criterion. When both sand and clay material are present, the plume length which can be modeled gives an unsatisfactory picture of the fate of the finer material. What has proved to be useful is to remove the coarser fraction from the distribution and repeat the computation with an appropriately larger distance between longitudinal stations. This practice is acceptable because the various fractions are assumed to behave independently in the model.

Conclusions

22. Much more sophisticated models of sediment diffusion processes are available. However, these models require a substantial body of field information which must be obtained for each specific problem, and also require a substantial investment in manpower and large computer costs for calibration

and testing. In some instances the data simply aren't available and/or the cost of obtaining them and applying a sophisticated model is unwarranted. The model described in this report gives a realistic general picture of plume behavior and should be particularly useful when the use of more sophisticated models is impractical.

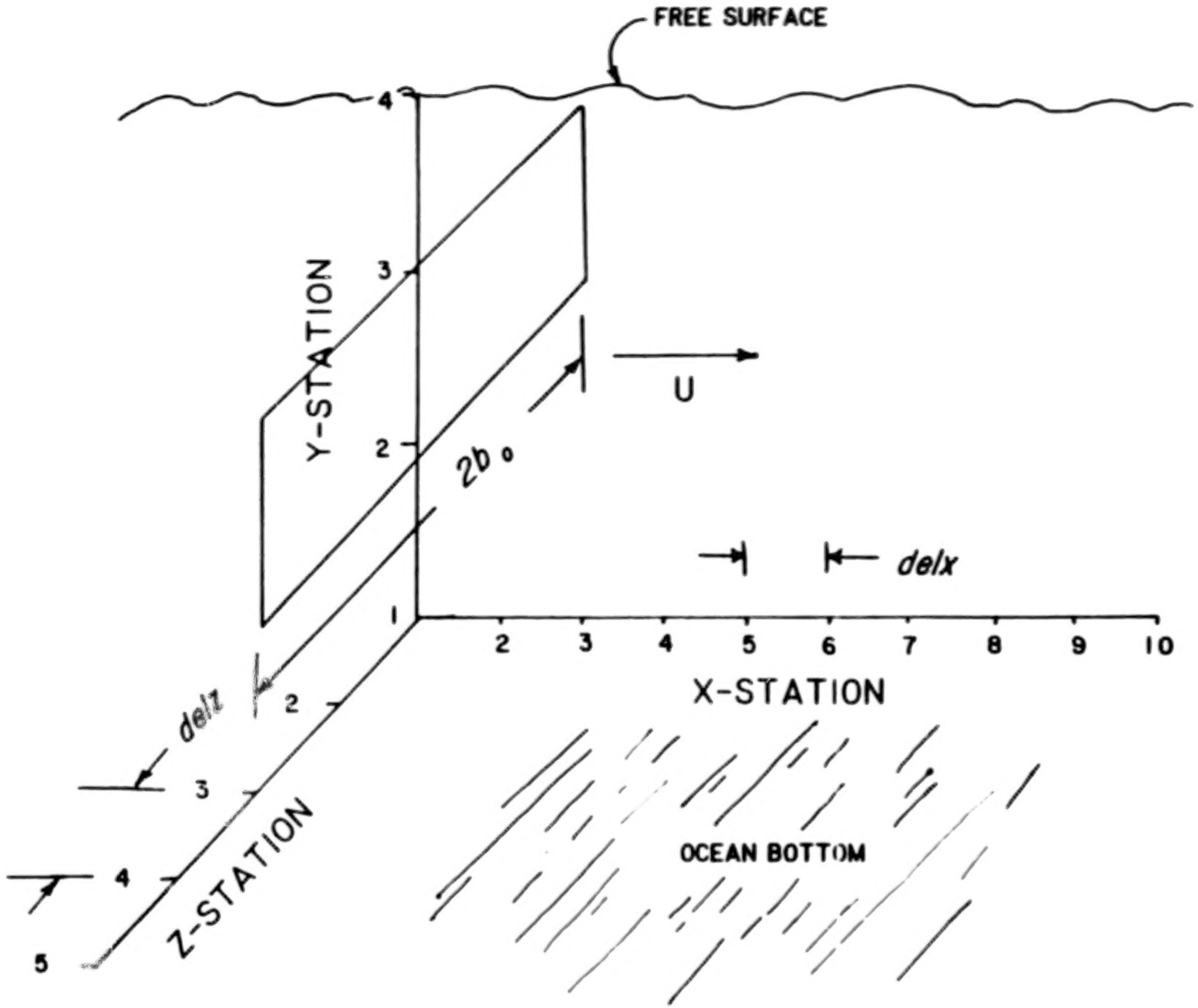

FIGURE I. DEFINITION SKETCH

Appendix A: Listing of Model

```
      INTEGER FORMFD,LF
      INTEGER*1 OPT,YORN
      DOUBLE PRECISION D(21,21),USTR,FX,FNYS2,UDX,E,EM,EP,B(21)
      DIMENSION CD(61,11),C(21),FLUX(6,61),V(5),CO(21,61),COT(21,61
      DIMENSION VCOB(61,6),NUM(10)
      DIMENSION DPTH(21),XDIS(61),ZDIS(11)
      DATA FORMFD/12/,CD/441*0./,COT/441*0.0/,LF/10/

   11 FORMAT(19X,F10.0)
    1 FORMAT(20X,F10.0)
    2 FORMAT(20X,I10)
    3 FORMAT(29X,A1)
    4 FORMAT(' FRACT. NUM. ',I2,' % OF MASS = ',F4.0,
     1         'FALL VELOCITY = ',F10.5)

      DO 10 N = 1,10
   10 NUM(N)=N
C
      WRITE(2,6030) FORMFD
C
      CALL OPEN (6,11HPLUME   VRS,1)
      READ(6,11)U
      READ(6,1)H
      READ(6,1)FR
      WRITE(2,5)U,FR,H
    5 FORMAT(' U = ',F10.5,' FR = ',F10.5,' H = ',F10.5)
      READ(6,1)DELX
      READ(6,1)DELZ
      WRITE(2,6)DELX,DELZ
    6 FORMAT(' DELX = ',F10.1,' DELZ = ',F10.1)

      READ(6,2)NXS
      READ(6,2)NYS
      READ(6,2)NZS
      WRITE(2,7)NXS,NYS,NZS
    7 FORMAT(' NXS = ',I4,' NYS = ',I4,' NZS = ',I4)

      READ(6,1)TWOBO
                  BO = TWOBO/2.
                  BO = BO
      WRITE(2,8)TWOBO
      READ(6,2)IBOTW
      WRITE(2,9)IBOTW
      READ(6,2)ITOPW
      WRITE(2,13)ITOPW
     8 FORMAT(' WIDTH OF WINDOW = ',F10.1)
     9 FORMAT('        Y NODE BOTTOM OF WINDOW = ',I5)
    13 FORMAT('        Y NODE AT TOP OF WINDOW = ',I5)

      READ(6,3)OPT
      WRITE(2,15)OPT,OPT
   15 FORMAT(' OPT = ',A1,2X,I3)
      IF(OPT .NE. 77) GO TO 20
      READ(6,1)FLUXO
      FNYS=NYS-1
      DELH=H/FNYS
      IF(IBOTW.EQ.1)IBOTW=2
      IF(ITOPW.EQ.NYS)ITOPW=NYS-1
      HW= FLOAT(ITOPW-IBOTW)/FNYS
      IF(HW.LT.0.5)HW=1
      HW=HW*DELH
      AW=TWOBO*HW
      CONCO=FLUXO/(U*AW)
      WRITE(2,19)CONCO
 19   FORMAT(' CONC. AT U_S BOUNDARY = ',1PE12.3)
      FNYS=FLOAT(NYS-2)
      RATIO = FLOAT(ITOPW-IBOTW+1)/FNYS
      CONC = FLUXO/(U*TWOBO*H*RATIO)
      GO TO 30

 20   READ(6,1)CONC

C
 30   CONTINUE
      XDIS(1)=0.
      DO 32 I = 2,NXS
 32   XDIS(I)=XDIS(I-1)+DELX
      ZDIS(1)=0.
      DO 34 I = 2,NZS
 34   ZDIS(I)=ZDIS(I-1)+DELZ
      FNYS1= NYS-1
      FNYS2= NYS-2
      DELH=H/FNYS1
      DELY=DELH
      DPTH(NYS)=0.
      J=NYS
      DO 36 I = 2,NYS
      J=J-1
      DPTH(J)=DPTH(J+1) + DELH
 36   CONTINUE

      WRITE(2,21)CONC
 21   FORMAT(' GROSS INITIAL CONCENTRATION = ',F10.2)
C
C
      READ(6,2)NFRACS
      WRITE(2,23)NFRACS
 23   FORMAT(' NUMBER OF MASS FRACTIONS = ',I2)
C
C
      DO 99 I=1,NYS
      DO 99 J=1,NXS
 99   COT(I,J)=0.

      DO 1000 L=1,NFRACS
         READ(6,1)PCNTMS
         READ(6,1)V(L)
         V(L)=V(L)/100.
C CONVERSION FRM CM/SEC TO M/SEC
               IF(V(L).GT.0)V(L)=-V(L)
               WRITE(2,4)L,PCNTMS,V(L)
               CONCFR =CONC*(PCNTMS/100.)
        NYS1=NYS-1
        DO 60 I =1,NYS
        IF(I.GE.IBOTW)GO TO 52
        CO(I,1)=0.
        GO TO 60
 52     IF(I.LE.ITOPW)GO TO 54
        CO(I,1)=0.
        GO TO 60
```

```
   54     CO(I,1)=CONCFR
   60     CONTINUE
C
C234567
        VRATIO=ABS(V(L))/U
        FNYS1 = NYS-1
        DELY  = H/FNYS1
        GRATIO=DELY/DELX
        IF(GRATIO.GE.VRATIO)GO TO 70
        WRITE(2,61)VRATIO,GRATIO
   61   FORMAT(' DELY/DELX MUST BE   OR = V/U FOR STABILITY '/
     1   ' V/U = ',F10.5,' DELY/DELX = ',F10.5,/
     2   ' DECREASE DELX OR  NYS... COMPUTATION ABORTED ')
        STOP
   70   CONTINUE
           USTR=SQRT(FR/8.)*U
           FX=0.4*USTR
           FNYS1=NYS-1
           FNYS2=NYS-2
           FNYS2=1./FNYS2
           DELY=H/FNYS1
           HDELY=0.5*DELY
           VDY=0.5*V(L)/DELY
           UDX=U/DELX
           SDYI=1./DELY**2
           DYI=1./DELY
           RATIO=(V(L)*DELX)/(U*DELY)
C
           DO 80 I=1,NYS
           DO 80 J=1,NYS
               D(I,J)=0.
     80    CONTINUE
C
           NYS1=NYS-1
C
           D(1,1)=-DYI
           D(1,2)=DYI
C
           DO 100 N=2,NYS1
                Y=(N-1)*DELY
                YM=Y-HDELY
                YP=Y+HDELY
                EM=FX*U*YM*(1.-YM/H)
                EP=FX*U*YP*(1.-YP/H)
                E=0.5*(EM+EP)
                D(N,N-1)=-EM*SDYI
                D(N,N)=UDX+2.*E*SDYI
                D(N,N+1)=-EP*SDYI
    100    CONTINUE
C
           D(NYS,NYS)=V(L)-EP*DYI
           D(NYS,NYS1)=+EP*DYI
C
           UDXI=1./UDX
           D(1,1)=UDXI*D(1,1)
           D(1,2)=UDXI*D(1,2)
C
           DO 200 I=2,NYS1
                D(I,I-1)=UDXI*D(I,I-1)
                D(I,I)=UDXI*D(I,I)
```

```
                   D(I,I+1)=UDXI*D(I,I+1)
  200    CONTINUE
C
         DO 300 I=2,NYS
              D(I,I-1)=D(I,I-1)/D(I-1,I-1)
              D(I,I)=D(I,I)-D(I,I-1)*D(I-1,I)
  300    CONTINUE
C
C
         N=1
         SUM=0.0
C
         DO 350 J=2,NYS1
  350    SUM=SUM+CO(J,N)
         FLUX(L,N)=2.*U*BO*H*SUM*FNYS2
C
         DO 800 N=2,NXS
              B(1)=0.
              DO 400 I=2,NYS1
                   B(I)=CO(I,N-1)-RATIO*(CO(I+1,N-1)-CO(I,N-1))
  400         CONTINUE
C
              B(NYS)=0.
              DO 500 I=2,NYS
                   B(I)=B(I)-D(I,I-1)*B(I-1)
  500         CONTINUE
C
              B(NYS)=B(NYS)/D(NYS,NYS)
              I=NYS
              DO 600 K=2,NYS
                   I=I-1
                   B(I)=(B(I)-D(I,I+1)*B(I+1))/D(I,I)
  600         CONTINUE
C
              DO 700 I=1,NYS
  700         CO(I,N)=B(I)
C
      VCOB(N,L)=-V(L)*CO(1,N)
C VCOB MAY BE THOUGHT OF AS HAVING THE DIMENSIONS
C GRAMS/SQ-METER PER SECOND IF ONE WILL REGARD
C CD AS DIMENSIONLESS

              SUM=0.0
              DO 750 J=2,NYS1
                 SUM=SUM+CO(J,N)
  750         CONTINUE
C
              FLUX(L,N)=2.*U*BO*H*SUM*FNYS2
C
  800    CONTINUE
C
         DO 820 I=1,NYS
         DO 820 J=1,NXS
         COT(I,J)=COT(I,J)+CO(I,J)
  820    CONTINUE
C
 1000 CONTINUE
C
      WRITE(3,881)
 881  FORMAT(' PRINT TABLE OF MASS FLUX  Y OR N    ? ')
```

```
      READ(3,882)YORN
  882 FORMAT(A1)
      IF(YORN .EQ. 78)GO TO 895
      WRITE(2,6030)FORMFD
      WRITE(2,883)
      WRITE(2,507)
      WRITE(2,508)
      WRITE(2,501)(NUM(I),I=1,NFRACS)
  883 FORMAT(5X,' TOTAL MASS FLUX AND FLUX FOR FRACTIONS ')
  507 FORMAT(5X,'                  GRAMS/SEC '/)
  508 FORMAT('   X       TOTAL     FRACTION NUMBER ')
  501 FORMAT(' METERS   FLUX       ',I5,5I10)
  884 FORMAT('  X(METERS) ')
      DO 890 N=1,NXS
         SUM=0.
         DO 870 L=1,NFRACS
               SUM=SUM+FLUX(L,N)
  870    CONTINUE
C
         WRITE(2,887)XDIS(N),SUM,(FLUX(L,N),L=1,NFRACS)
  887 FORMAT(1X,F8.0,1PE10.2,1PE10.2,1PE10.2,1PE10.2,1PE10.2,
     1        1PE10.2,1PE10.2,1PE10.2,1PE10.2,1PE10.2,1PE10.2)
  890  CONTINUE
  895  CONTINUE
C
C234567
      WRITE(3,891)
  891 FORMAT(' PRINT SUM OF CO TABLE (Y OR N) ? ')
      READ(3,882)YORN
      IF(YORN .EQ. 78)GO TO 955
      JDEL=(NYS-1)/4
      JYS=1+JDEL*4
      IF (JYS .EQ. NYS) GO TO 899
      WRITE(3,951)
  951 FORMAT(' NO. OF Ys MUST EQUAL 5,9,13... TO PRINT THIS TABLE ')
      GO TO 955

  899 WRITE(2,6030)FORMFD
C
      WRITE(2,931)
  931 FORMAT(20X,'TABLE OF CO VALUES (MILLIGRAMS/LITER) '/)
      WRITE(2,932)(DPTH(I),I=1,NYS,JDEL)
  932 FORMAT(' DEPTH = ',F7.0,4F10.0)

      WRITE(2,884)
      DO 950 I =1,NXS
      WRITE(2,953)XDIS(I),(COT(J,I),J=1,NYS,JDEL)
  953 FORMAT(1X,F8.0,1PE10.2,1PE10.2,1PE10.2,1PE10.2,1PE10.2)
  950 CONTINUE
  955 CONTINUE
      WRITE (3,957)
  957 FORMAT (' COMPUTING CD, PLEASE WAIT '//)

      CD(1,1)=1.0
      DO 1050 I = 2,NZS
 1050 CD(I,I)=0.0

      EZ=0.2*H*USTR
      DO 1200 N=2,NXS
         X=(N-1)*DELX
```

```
          AL=SQRT(U/(4*X*EZ))
C
          DO 1100 J=1,NZS
                Z=(J-1)*DELZ
                ARG1=AL*(BO+Z)
                ARG2=AL*(BO-Z)
                ERF1=ERF(ARG1)
                IF (ARG2 .LT. 0.) GO TO 441
                ERF2=ERF(ARG2)
                CD(N,J)=0.5*(ERF1+ERF2)
                GO TO 1100
 441           ERF2=ERF(-ARG2)
                CD(N,J)=0.5*(ERF1-ERF2)
 1100     CONTINUE
C
 1200 CONTINUE
      WRITE(3,1201)
 1201 FORMAT(' PRINT TABLE OF CD VALUES <Y OR N> ? ')
      READ(3,882)YORN
      IF(YORN.EQ.78)GO TO 1300
      WRITE(2,6030)FORMFD
      WRITE(2,1202)
 1202 FORMAT(20X,' TABLE OF CD VALUES ')
      WRITE(2,1203)(ZDIS(I),I=1,NZS)
 1203 FORMAT('  Z = ',11F10.0)
      WRITE(2,884)
      DO 1250 I = 1,NXS
      WRITE(2,887)XDIS(I),(CD(I,J),J=1,NZS)
 1250 CONTINUE
 1300 CONTINUE
 6030 FORMAT (A4)
C
      WRITE(3,1301)
 1301 FORMAT(' TO GENERATE A TABLE OF CONCENTRATTION: '/
     1        ' ENTER THE DEPTH AT WHICH CONCENTRATION IS WANTED '/
     2        ' TO STOP GENERATING CONCENTRATION TABLES: '/
     3        ' ENTER A NEGATIVE NUMBER '//
     4        ' <DEPTHS ARE ROUNDED TO THE NEAREST NODAL ELEVATION> '/)
 1320 CONTINUE
      WRITE(3,1302)
 1302 FORMAT(' DEPTH IN METERS = ? ')
      READ(3,1303)DEPTH
 1303 FORMAT(F10.0)
      IF(DEPTH .LT. 0.)GO TO 1400
      WRITE(2,6030)FORMFD
      IY = DEPTH/DELH
      REM = DEPTH -FLOAT(IY)*DELH
      IF(REM.GT.0.5*DELH)IY=IY+1
      DEPTH = FLOAT(IY)*DELH
      WRITE(2,1304)
 1304 FORMAT(20X,' TABLE OF CONCENTRATIONS (MILLIGRAMS/LITER) ')
      WRITE(2,1305)DEPTH
      WRITE(2,1203)(ZDIS(I),I=1,NZS)
      WRITE(2,884)
      IY = NYS - IY
      DO 1380 N = 1,NXS
      DO 1340 I = 1,NZS
 1340 C(I) = COT(IY,N)*CD(N,I)
      WRITE(2,887)XDIS(N),(C(I),I=1,NZS)
 1380 CONTINUE
 1305 FORMAT(25X,' AT A DEPTH OF ',F5.0,' METERS '/)
      GO TO 1320
 1400 CONTINUE

      WRITE(3,1401)
 1401 FORMAT(' PRINT TABLE OF DEPOSITION RATES <Y OR N> ? ')
      READ(3,882)YORN
      IF(YORN.EQ.78)GO TO 1500
      WRITE(2,6030)FORMFD
      WRITE(2,1402)
 1402 FORMAT(20X,' TABLE OF DEPOSITION RATES ')
      WRITE(2,1403)
 1403 FORMAT(20X,'    (GRAMS/SEC PER M-SQ )'/)
      WRITE(2,1203)(ZDIS(J),J=1,NZS)
      WRITE(2,884)
      DO 1460 I = 1,NXS
      SUM =0.
      DO 1420 K = 1,NFRACS
      SUM = SUM+VCOB(I,K)
 1420 CONTINUE
      DO 1440 J = 1,NZS
 1440 C(J)=SUM*CD(I,J)
C IN THIS CONTEXT C(J) IS A CONVENIENT DUMMY
      WRITE(2,887)XDIS(I),(C(J),J=1,NZS)
 1460 CONTINUE
 1500 CONTINUE

      STOP
      END
C
      FUNCTION ERF(X)
C
      DOUBLE PRECISION A1,A2,A3,A4,A5,T,P
      DATA A1,A2,A3 /.254829592,-.284496736,1.421413741/
      DATA A4,A5    /-1.453152027,1.061405429/
C
      EXPF=0.0
      IF (X .GT. 4.2) GO TO 10
      T=1./(1.+.3275911*X)
      P=((((A5*T+A4)*T+A3)*T+A2)*T+A1)*T
      EXPF=EXP(-X*X)
   10 ERF=1.-P*EXPF
C
          RETURN
          END
```

Appendix B: Listing of FRNT

```
      PROGRAM FRNT
      INTEGER*1 FLD(20)
      INTEGER*1 CR,LF,ZERO
      INTEGER*1 VN
      CR=13
      LF=10
      ZERO = 48

      CALL OPEN(7,11HPLUME   VRS,1)

      WRITE(3,3)
      CALL GETFLD(FLD)
    3 FORMAT(' STREAM VELOCITY (M/SEC) = ? ')
      WRITE(7,4)(FLD(I),I=1,20)

      WRITE(3,7)
    7 FORMAT(' DEPTH IN METERS = ? ')
      CALL GETFLD(FLD)
      WRITE(7,8)LF,(FLD(I),I=1,20)

      WRITE(3,9)
    9 FORMAT( ' FRICTION FACTOR (RANGE = 0.0005 TO 0.025) = ? ')
      CALL GETFLD(FLD)
      WRITE(7,10)LF,(FLD(I),I=1,20)

      WRITE(3,11)
   11 FORMAT(' LONGITUDIONAL DIST. BETWEEN STATIONS IN METERS = ? ')
      CALL GETFLD(FLD)
      WRITE(7,12)LF,(FLD(I),I=1,20)

      WRITE(3,13)
   13 FORMAT(' LATERAL DIST. BETWEEN STATIONS IN METERS = ? ')
      CALL GETFLD(FLD)
      WRITE(7,14)LF,(FLD(I),I=1,20)

      WRITE(3,15)
   15 FORMAT(' NUMBER OF STATIONS IN LONGITUDIONAL DIRECTION = ? ')
      CALL GETFLD(FLD)
      WRITE(7,16)LF,(FLD(I),I=1,20)

      WRITE(3,17)
   17 FORMAT(' NUMBER OF STATIONS IN THE VERTICAL DIRECTION = ? ')
      CALL GETFLD(FLD)
      WRITE(7,18)LF,(FLD(I),I=1,20)

      WRITE(3,19)
   19 FORMAT(' NUMBER OF STATIONS IN THE LATERAL DIRECTION = ? ')
      CALL GETFLD(FLD)
      WRITE(7,24)LF,(FLD(I),I=1,20)

      WRITE(3,27)
   27 FORMAT(' WIDTH OF INFLOW WINDOW (METERS) = ? ')
      CALL GETFLD(FLD)
      WRITE(7,38)LF,(FLD(I),I=1,20)

      WRITE(3,29)
   29 FORMAT(' STATION NUMBER FOR BOTTOM OF WINDOW ( 1 IS BOTTOM) = ? ')
      CALL GETFLD(FLD)
      WRITE(7,34)LF,(FLD(I),I=1,20)

      WRITE(3,31)
   31 FORMAT(' STATION NUMBER FOR TOP OF WINDOW ( =< NUMB. OF Ys) = ? ')
      CALL GETFLD(FLD)
      WRITE(7,36)LF,(FLD(I),I=1,20)

      WRITE(3,33)
   33 FORMAT(' MASS FLUX OR CONC. BOUN_COND (M OR C) ? ')
      CALL GETFLD(FLD)
      WRITE(7,42)LF,(FLD(I),I=1,20)
      VN = FLD(20)

      IF(VN .EQ. 77)GO TO 80
      WRITE(3,35)
   35 FORMAT( ' CONCENTRATION (GRAMS/LITER) = ? ')
      CALL GETFLD(FLD)
      WRITE(7,44)LF,(FLD(I),I=1,20)

      GO TO 90
   80 CONTINUE

      WRITE(3,21)
   21 FORMAT(' MASS FLUX (IN UNITS OF GRAMS/SEC) = ? ')
      CALL GETFLD(FLD)
      WRITE(7,26)LF,(FLD(I),I=1,20)

   90 CONTINUE

      WRITE(3,23)
   23 FORMAT(' NUMBER OF SEDIMENT SIZE FRACTIONS (1 TO 9) = ? ')
      CALL GETFLD(FLD)
      WRITE(7,28)LF,(FLD(I),I=1,20)

      NUM = FLD(20)-ZERO

      DO 100 NN = 1,NUM
      WRITE(3,25),NN
   25 FORMAT(' % OF MASS  FOR FRACTION',I2,' (0 TO 100) = ? ')
      CALL GETFLD(FLD)
      WRITE(7,32)LF,(FLD(I),I=1,20)

      WRITE(3,5)NN
    5 FORMAT(' SETTLING VELOCITY FOR FRACTION',I2,' (CM/SEC) = ? ')
      CALL GETFLD(FLD)
      WRITE(7,6)LF,(FLD(I),I=1,20)


  100 CONTINUE

C                 12345678
    4 FORMAT(' U       = ',20A1)
    6 FORMAT(A1,'     V   = ',20A1)
    8 FORMAT(A1,' H      = ',20A1)
   10 FORMAT(A1,' FF     = ',20A1)
   12 FORMAT(A1,' DELX   = ',20A1)
   14 FORMAT(A1,' DELZ   = ',20A1)
   16 FORMAT(A1,' NXS    = ',20A1)
   18 FORMAT(A1,' NYS    = ',20A1)
   24 FORMAT(A1,' NZS    = ',20A1)
   26 FORMAT(A1,' FLUX   = ',20A1)
   28 FORMAT(A1,' NFRCS = ',20A1)
   32 FORMAT(A1,' PCTMF = ',20A1)
   34 FORMAT(A1,' WBOT  = ',20A1)
   36 FORMAT(A1,' WTOP  = ',20A1)
   38 FORMAT(A1,' 2*B0  = ',20A1)
   42 FORMAT(A1,' OPT   = ',20A1)
   44 FORMAT(A1,' CONC  = ',20A1)
   46 FORMAT(A1)

      WRITE(7,46)LF
      STOP
      END
      SUBROUTINE GETFLD(FLD)
      INTEGER*1 CHARS(80),FLD(20),SP
      READ(3,1)(CHARS(I),I=1,80)
    1 FORMAT(A1,80A1)
        NCHARS = 80
      CALL COUNT(CHARS,NCHARS)
      CALL FIELD(CHARS,FLD,NCHARS)
      RETURN
      END
      SUBROUTINE COUNT(CHARS,NCHARS)
      INTEGER*1  CHARS(80),SP
      SP = 32
      NCHARS = 80
      DO 20 I = 1,80
      NCHARS = NCHARS - 1
      IF(CHARS(NCHARS).NE.SP)GO TO 40
   20 CONTINUE
   40 CONTINUE
      RETURN
      END
      SUBROUTINE FIELD(CHARS,FLD,NCHARS)
      INTEGER*1  CHARS(80),FLD(20)
      INTEGER*1  SP
      SP = 32
      NSPS = 20 - NCHARS
      DO 20 I = 1,NSPS
      FLD(I) = SP
   20 CONTINUE
      DO 40 I = 1,NCHARS
      N = I + NSPS
      FLD(N) = CHARS(I)
   40 CONTINUE
      RETURN
      END
```

END

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